Search of GW optical counterpart in the Multi-Messenger Astronomy Era

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INAF-Napoli
INFN –Napoli
&
GRAWITA team

Credit: NASA's Goddard Space Flight Center/CI Lab

GRAWITA project

GRAWITA goals

The present research group is committed to taking part in the search and the study of electromagnetic counterparts of the GW events by using observational facilities.

Know how

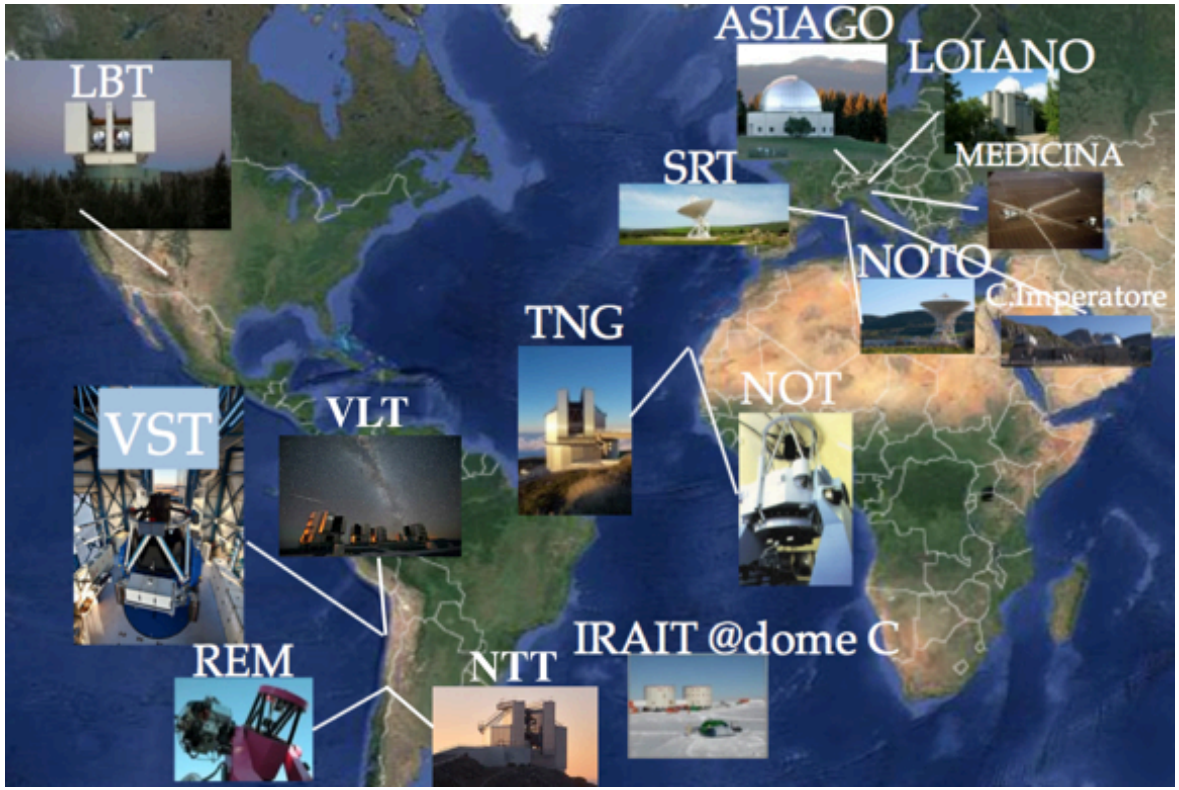
Time Domain Astronomy, Observational Strategy, Wide field images, Image analysis, Accurate Photometry in crowded fields, GRB astronomy, Supernovae, Data Interpretation, Theoretical models

Who we are ~ 80 people

INAF OA Roma: **E. Brocato (P.I.)**, L.A. Antonelli, S. Ascenzi, P. Casella, G. Israel, G. Iannicola, M. Lisi, S. Piranomonte, L. Pulone, L. Stella, A. Stamerra, V.Testa, R. Carini, A. Di Paola, A. Giunta
INAF OA Napoli: **A. Grado**, M Botticella, M. Capaccioli, M. della Valle, F. Getman, L. Limatola, P. Schipani
INAF OAS Bologna: **L. Nicastro**, L. Amati, A. Bulgarelli, M. Dadina, G. De Cesare, N. Masetti, E. Palazzi, A. Rossi, D. Vergani, D. Romano, E. Maiorano,
INAF OA Brera: **S. Campana**, S. Covino, P. D'Avanzo, A. Melandri, G. Tagliaferri, G. Ghirlanda, G. Ghisellini, M. Bernardini
INAF OA Padova: **E. Cappellaro**, S. Benetti, L. Tomasella, M. Turatto, S. Yang, R. Ciolfi, M. Mapelli, M. Spera
GSSI: **M. Branchesi**
***Uni Urbino*: G. Greco**, G. Stratta
Uni Bologna: A. Cimatti, M. Moresco, M. Talia, M. Brusa, G. Lanzuisi
***INAF IASF Milano*:** R. Salvaterra
Uni. Pisa: B. Patricelli, M. Razzano
***ASI Science Data Center*: V. D'Elia**, G. Giuffrida, S. Marinoni, P. Marrese
INAF Cagliari: A. Possenti, M. Burgay, E. Molinari
INAF OA Abruzzo: **M. Cantiello**, G. Raimondo
UNI Calabria: S. Savaglio
INFN Trieste: F. Longo
Uni. Trieste: F. Matteucci,
Uni Milano: A. Perego, O. Salafia
INAF OA Trieste: R. Cescutti

Multi-wavelengths Facilities Network

***Visible**: VST, LBT, TNG, NOT (coll.), NTT, VLT + small telescopes [REM, 1.82m (Asiago, IT), 1.52m (Loiano, IT), 0.9m C. Imperatore, IT)] + HST (coll.)*
***Near-mid IR**: 1.1m AZT-24 (C. Imperatore,IT), IRAIT (Antarctica)*
***Radio**: 64m SRT (Cagliari, IT), 2x 32m (Medicina and Noto, IT)*



***Collaborations**: ePESSTO*
***Positive interactions during O1+O2**: Pan-Starrs, iPTF, VISTA, HST …..*

Why search for EM counterpart

GW

- Mass
- Spins
- Eccentricity
- NS compactness
- System orientation
- Luminosity distance

- Identify host galaxy
- Constraints on progenitors
- H_0
- GW speed
- GR tests
- Formation scenario
- Massive stars evolution

EM

- Energetics and beaming
- Sky localization (arcsec)
- Host galaxy
- environment
- Redshift
- Nuclear astrophysics

Multi-messenger astronomy

We focus on:

GW:

compact binary coalescence (CBC)

EM:

photons in optical near infrared band

GWs from compact objects

Source type? How far? How many? Localization?

Source type	Detectors sensitivity O3 (Mpc)	Estimated # of detections in O3 (in 12 months)	localization
NS-NS	120-170 (LIGO) 65-85 (Virgo)	1-50[1]	20-26 % in 5 deg^2 42-50 % in 20 deg^2
NS-BH	190-270 (LIGO) 100-140 (Virgo)	1-2[3,4]	~ BNS
BBH	1110-1490 (LIGO) 610-1030 (Virgo)	6 - 130[2]	Tens to hundreds deg^2

Abbott et al 2018 Liv. Rev. Relat. 21;3

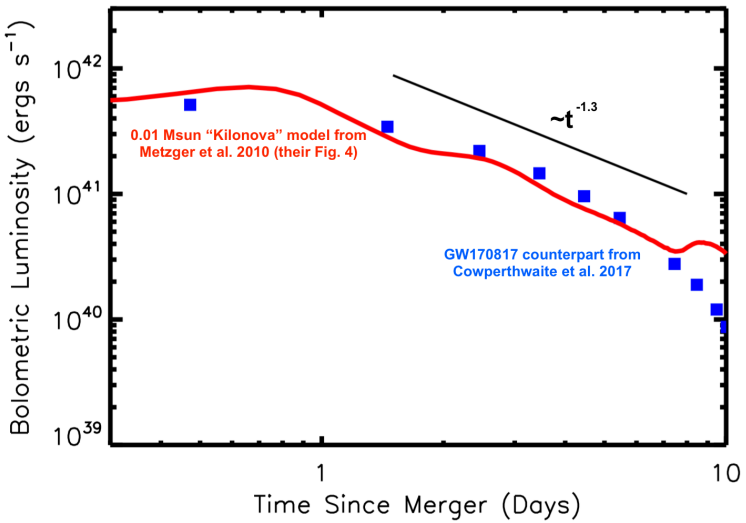
[1]Assuming a rate of 10^{-8} - 10^{-5} Mpc^{-3} yr^{-1} (Abbott et al. 2017, PRL, 119, 161101)
[2]Rodriguez et al. 2016, PRD, 93,8, 084029 (rate 2-20 $Gpc^{-3}yr^{-1}$)
[3]Assuming an upper limit rate of $3.6x10^{-6}$ Mpc^{-3} yr^{-1}
[4]Pannarale et al. 2014 ApJ, 791, 5

EM emission from CBC

For binaries with at least one NS

Lattimer & Schramm 1974 (r-process)
Li & Paczynski 1998, Metzger 2010
(UV-Optical emission prediction),

For BNS we expect M_{AB} ~ -16 mag



Metzger 2017 arXiv:1710.0593

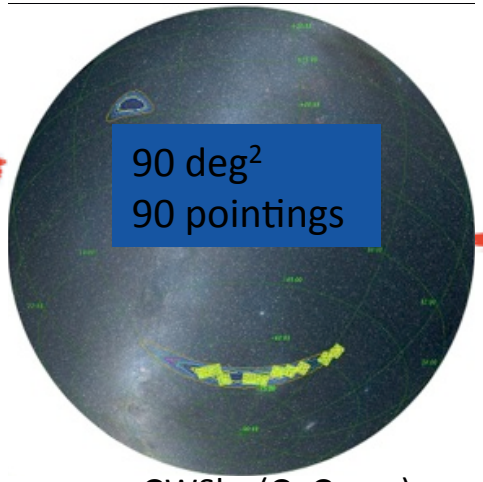
Rosswog et al. 1999, Perego et al. 2017 (material ejection mechanism) (see Albino talk)

For binary black holes

EM signal if a low mass circumbinary disk survives until the coalescence.
(de Mink et al. 2017) (Yamazaki et al. 2016)

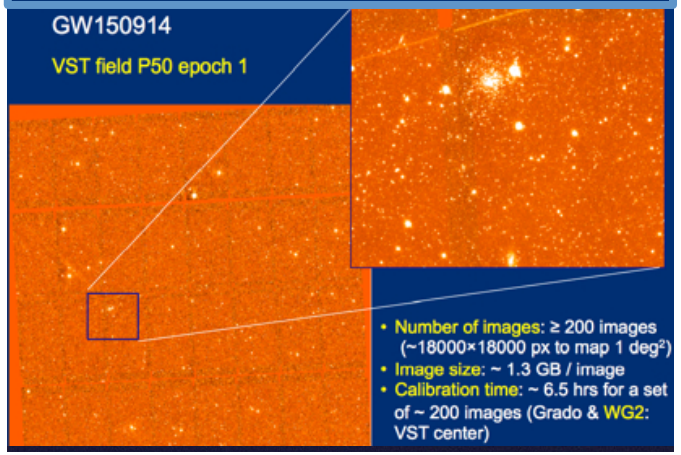
Alert

Observations preparation

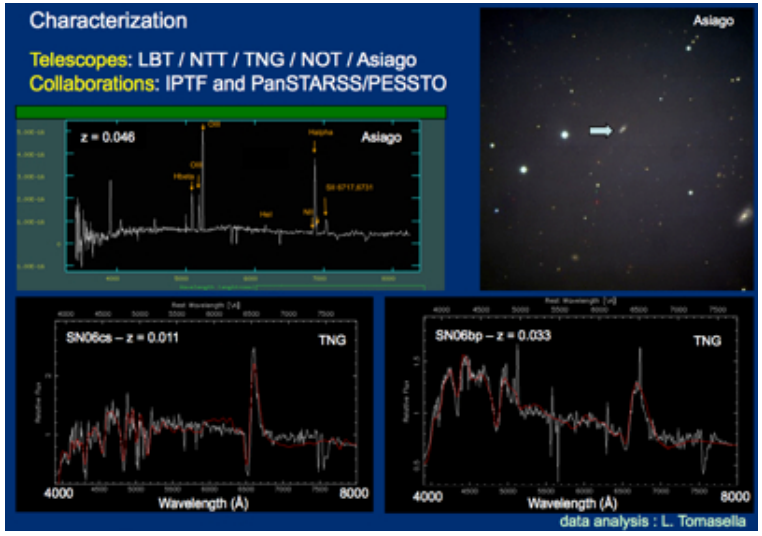


GWSky (G. Greco)

Observations+image reduction

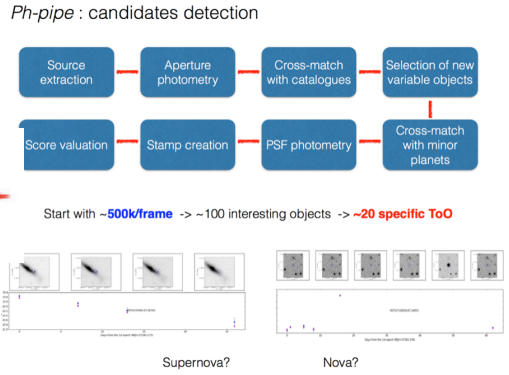


Characterization

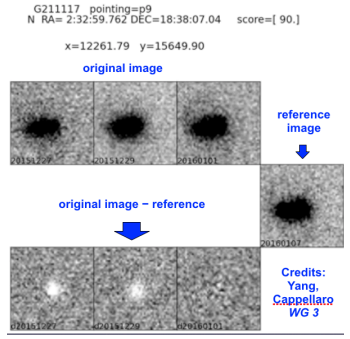


Pian et al. 2017

Search



Credit: S. Covino



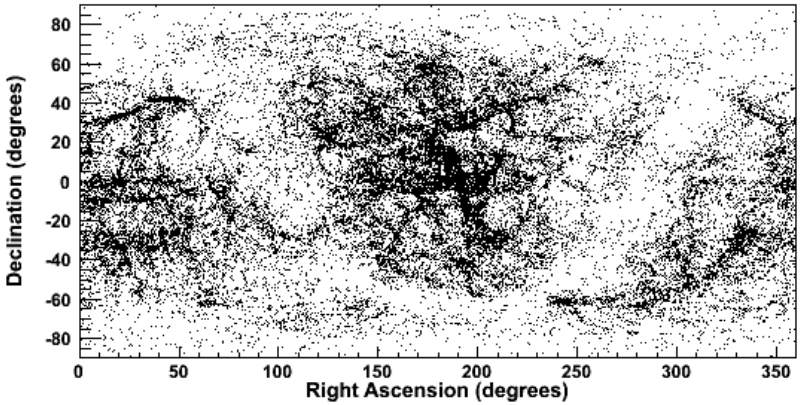
Credit: E. Cappellaro, S. Yang

Optical counterpart search problem statement

- Sky error area (3 detectors): 30-100 deg^2
- For BNS absolute magnitude ~ -16 mag
- Alert within tens of minutes (with human vetting)
- We want to find OC candidates as soon as possible for further spectroscopic follow-up

Two approaches:

- Targeted search
- blind search



White et al. 2011

Efficient search requires:

- Reference catalogs/images (Pan-Starrs, Slymapper, SDSS)
- Elimination of fore- and back-ground events (multi-epochs full sky surveys)

Observational strategy

Wide error area
+
nearby source

→ Targeted search

We need a complete galaxies catalog
GWGC (white 2011) complete up to 40 Mpc for M_B=-15 mag

Small to moderate
Error area
+
far source

→ Blind search

20 deg^2 error area ~200 Mpc define a volume with ~ 500 galaxies L > 0.1 x L_* (L_* ~ luminosity of Milky Way)

Blind search @VST

Two companion programs on GTO time (in reward of telescope and camera construction):

- On ***VST-GTO***: PI A. Grado
- On ***OmegaCam-GTO***: E. Cappellaro

We start with a negotiation with ESO to have the VST in Target of Opportunity (ToO) mode.

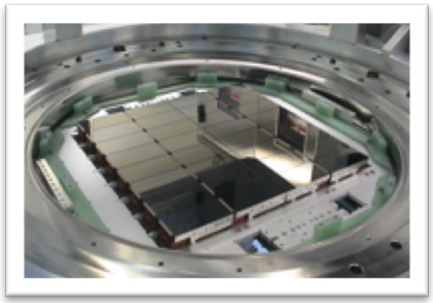
Since P95 (1 April-30 Sept 2015) ToO and follow-up programs.

Up to now allocated 240h on these surveys

VST in a nutshell

Located on Paranal Chile
In operation since October 2011

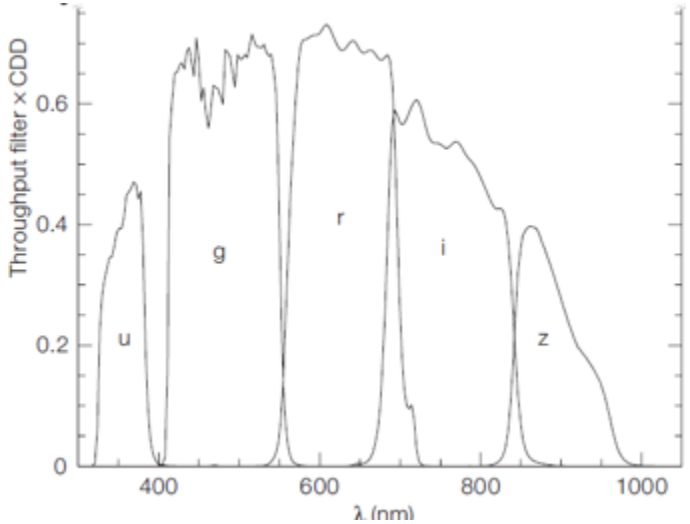
- Primary mirror: 2.6m
- 1.46 deg corrected FoV (∅)
- 80% EE in 0.4″



Camera OmegaCam

- 268 Mpixel 1°x1° FoV
- 0.21 arcsec/pixel
- 32 scientific CCDs + 4 outer CCDs

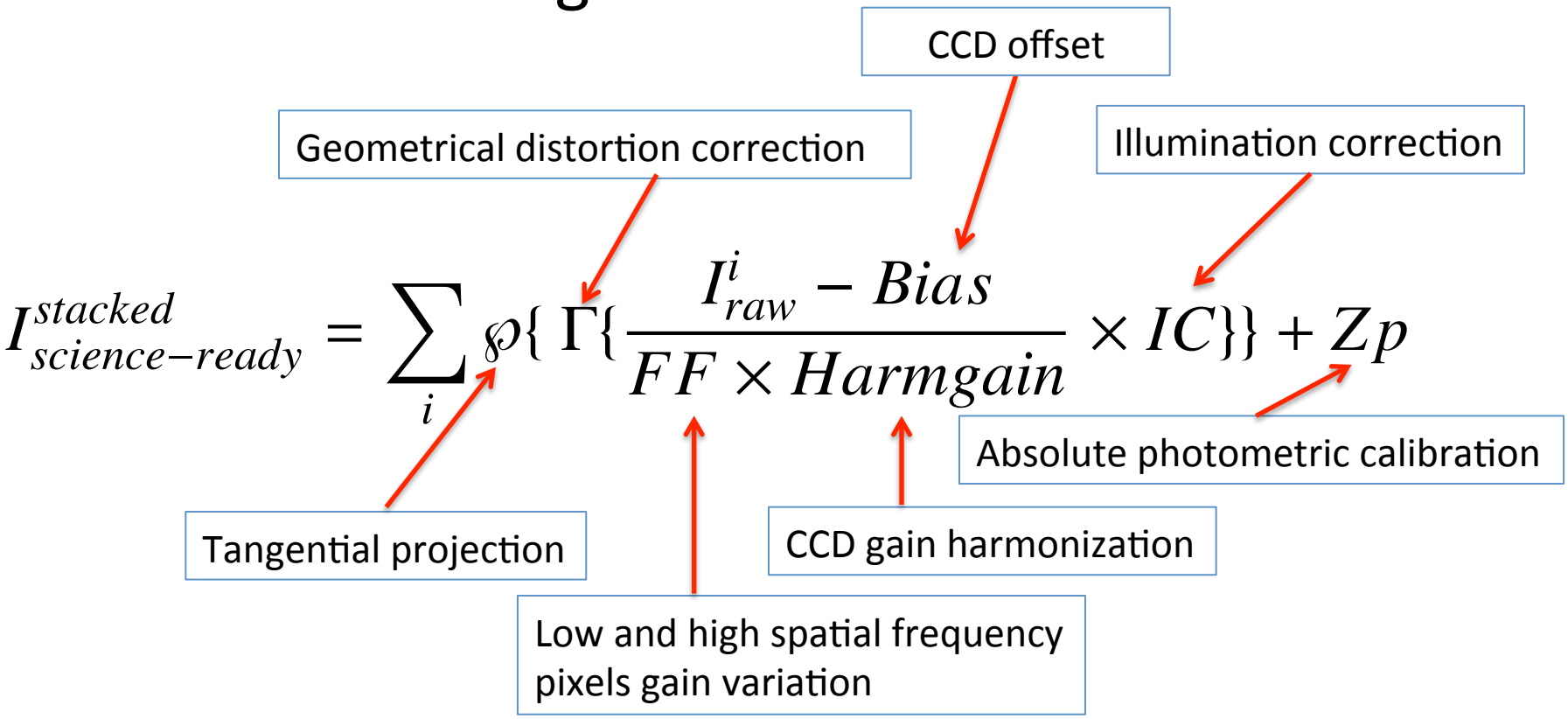
5 SDSS filters



Founds, design and construction @Osservatorio di Capodimonte

Processing astronomical images

Go from raw to instrumental signatures cleaned full calibrated images



VST images processed with VST-Tube pipeline (100.000 lines Python, C in house dev. code A. Grado et al. 2012 MSAIS, 19, 362)

GW150914 EM sky coverage

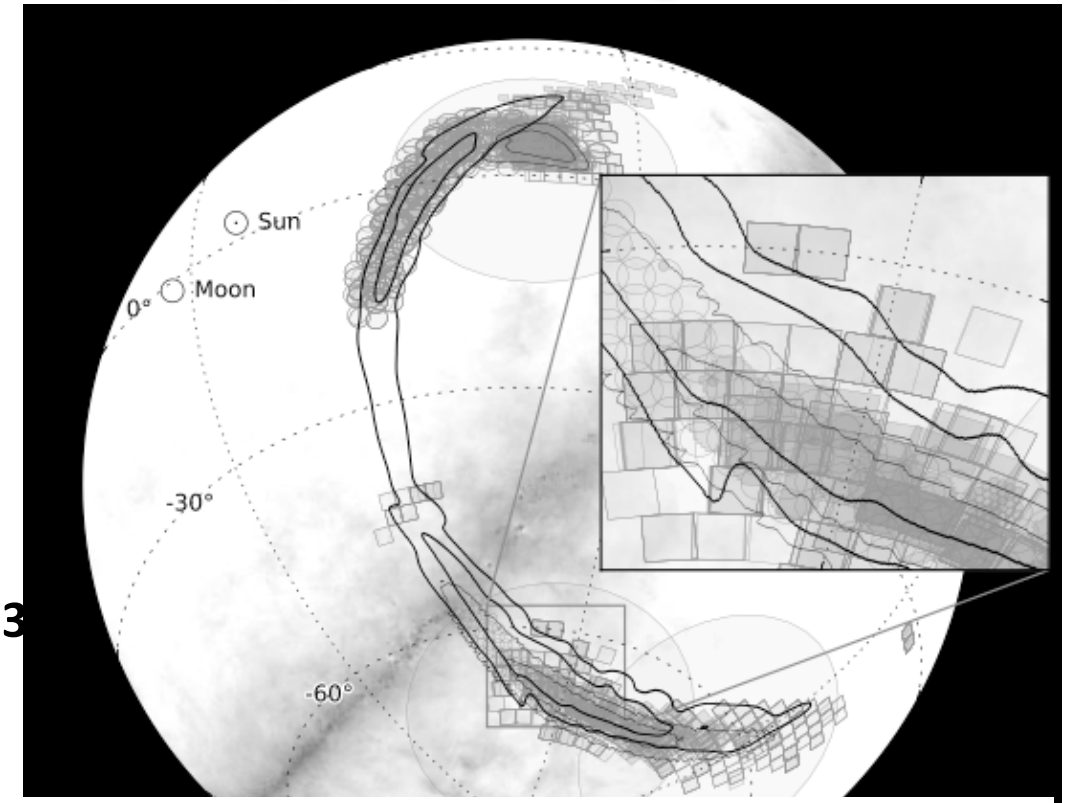
24 observatories involved !!

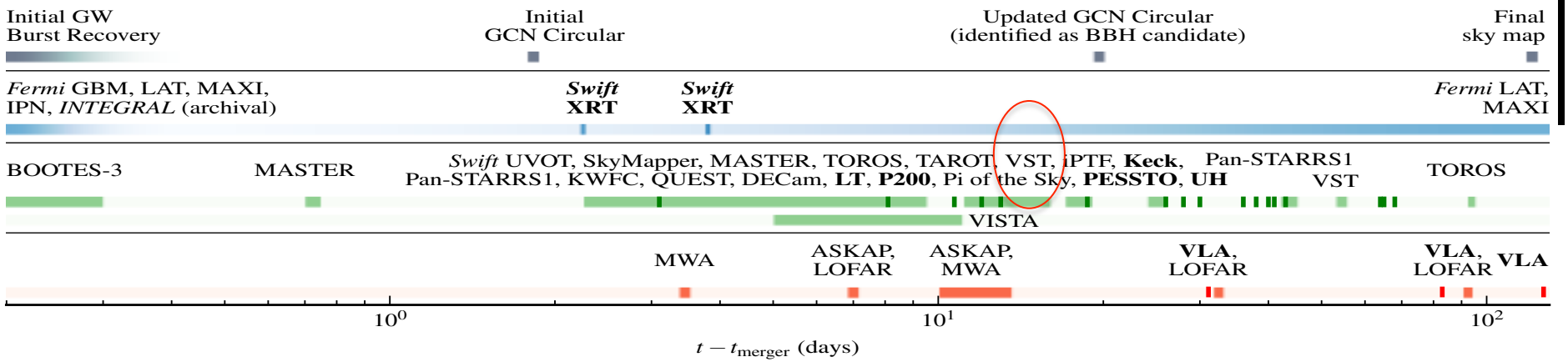
19 orders of magnitude in frequency space

+ neutrino search IceCube/ Antares (+/- 500s)

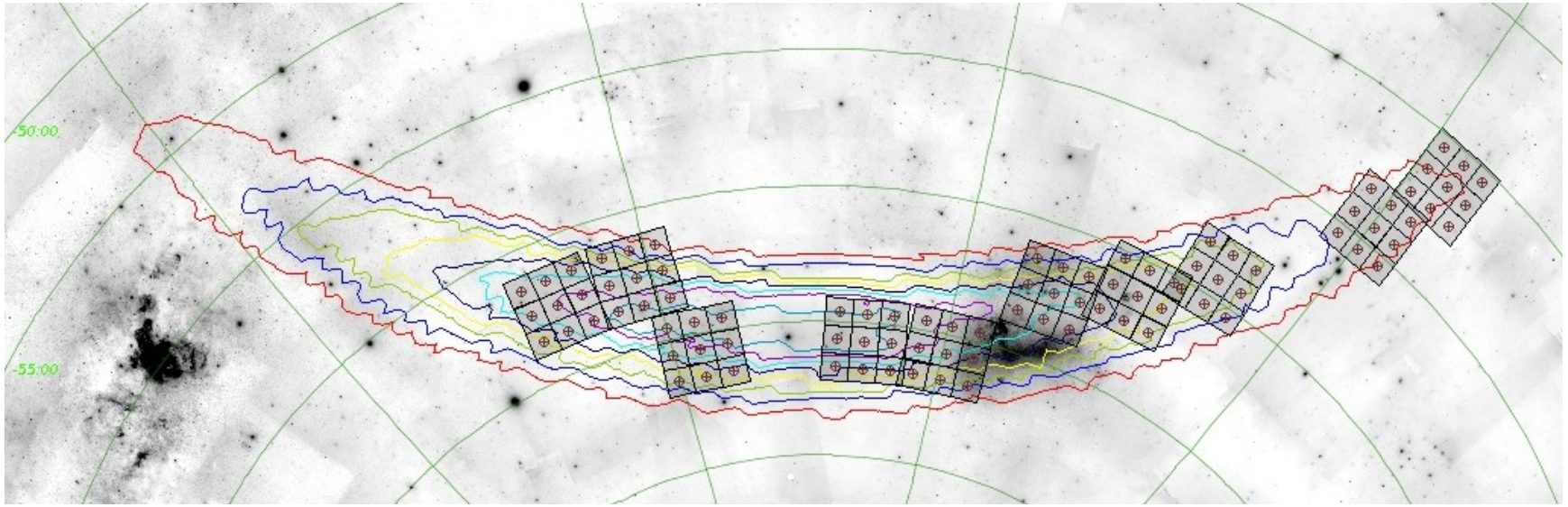
LVC-EM, APJL,826,1 L13,2016

Antares,IceCube, LVC, Phys. Rev. D**93** 122010,2016





First event GW150914



cWB sky location: red 90% enclosed probaility

Blocks of 3x3 deg^2

2x40 s dithered images (to fill ccds mosaic gaps)

90 deg^2 in 6 epochs (over 2 months)

29% of the localization probability for cWB sky map enclosed

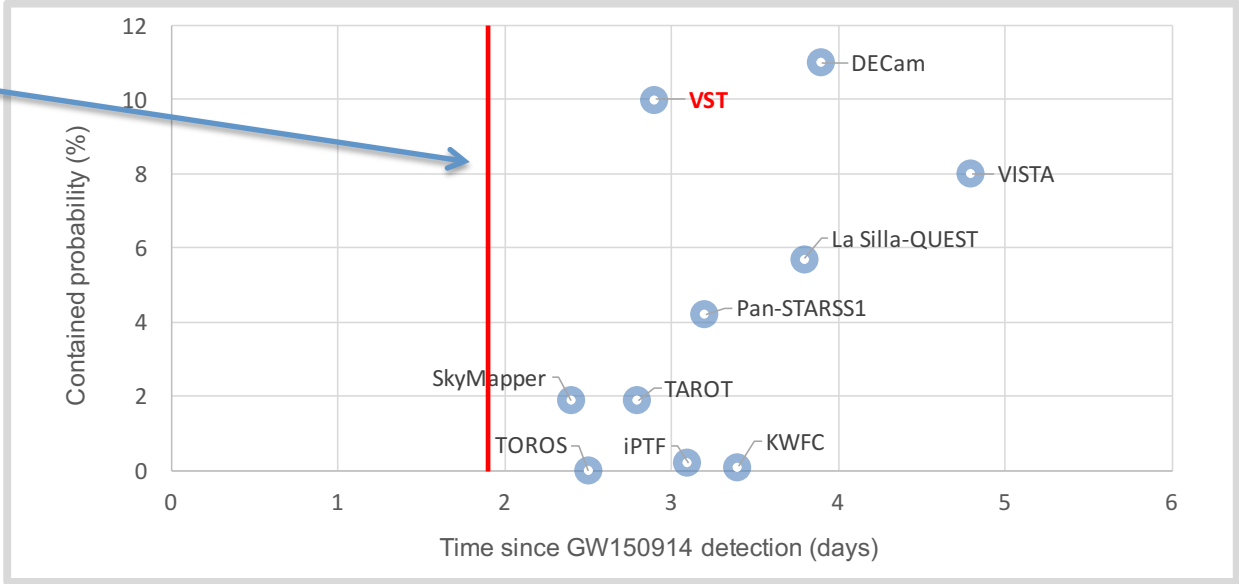
10% considering the LALinference sky map (shared with observers on 2016 January 13)

Pointings obtained with GWsky (Greco et al. in preparation)

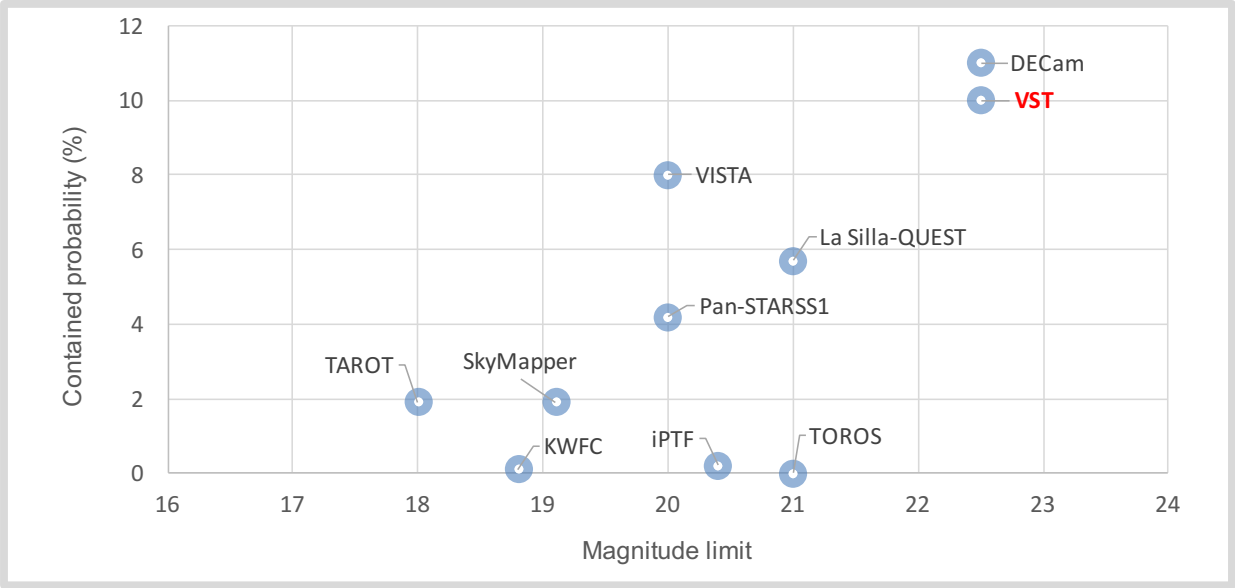
VST survey performance

LVC alert

Contained probability vs Time response



Contained probability vs limiting magnitude



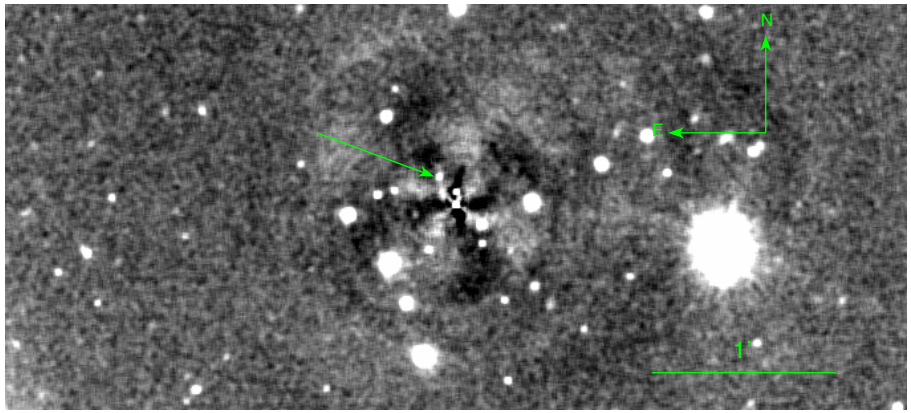
Data from Abbott et al 2016

Search counterpart with VST

Event	Latency (hours)	Filter -	Coverage Initial sky map (%)	Coverage refined sky map (%)	# of epochs - -	Completeness (AB mag)
GW150914	23	r	29	10	6	21
GW151226	7.6	r	9	7	6	21
GW170814	17.5	r	77	54	6	22 .5
GW170817	10.16	r	31	15	1	22.5
NGC4993	5.4d	g,r,i,z	-	-	1	23.6,23.5,22.5,21.8
NGC4993	14.4d	i	-	-	1	22.5
NGC4993	145.7d	g,i	-	-	1	25.0, 24.5

Smoothed residuals of isophotal elliptical fit

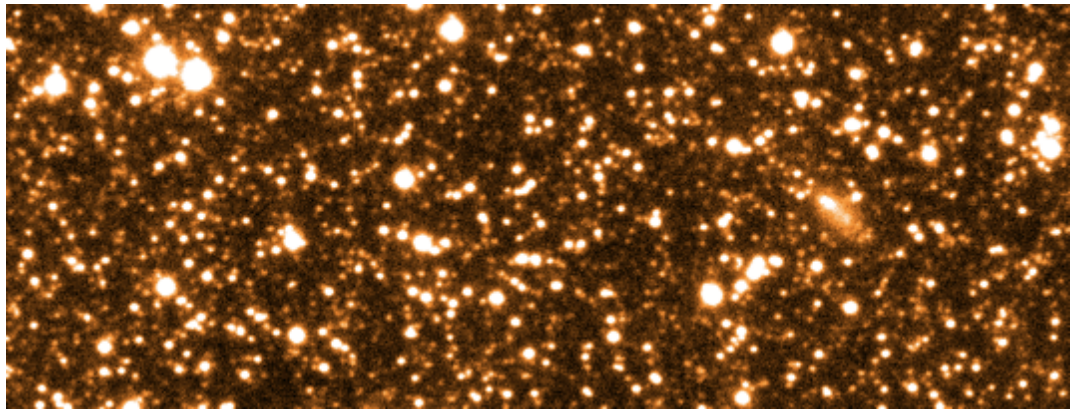
NGC4993 r filter



EM counterpart search: a very tough task

Find ONE transient in the GW error area. For the first two events 90% enclosed prob. ~ 200-1000 deg^2

- 10-50 SN
- > 100 AGN
- Thousand of variable stars
- Thousand of asteroids



In 1 deg^2 ~ 300k sources !!

Transients search in Grawita

Two complementary pipeline for transients search

- ***diff-pipe*** images subtraction (Cappellaro et al. 2015)

  PRO: deeper (with good seeing, transients detected up to r=22 mag AB), for crowded fields, source embedded in extended objects;

  CON: slow, more sensible to images defects

- ***phot-pipe*** (S. Covino) comparison among epochs in catalog space

  PRO: fast;

  CON: shallower, missing transients in extended sources…

Results for GW150914 event

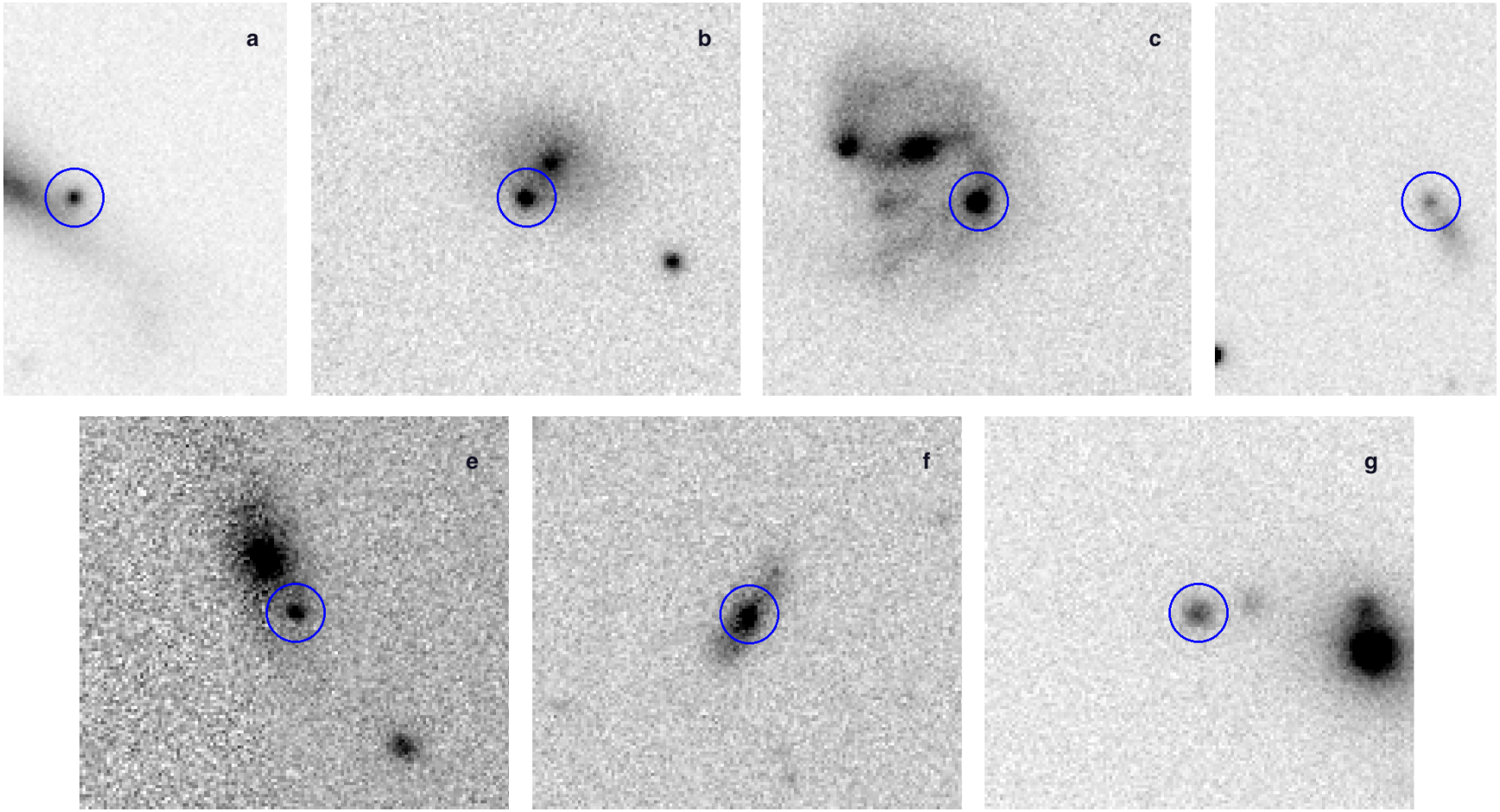
	Diff-pipe	Phot-pipe
Initial number of sources in all epochs	9,000,000	9,000,000
Initial # of candidates	170,000	54,239
Total # of transients	8,000	939
# known variables	6722	
# of known SN in the field/detected	4/4	
# new SN candidates	7	

Brocato et al. 2018 MNRAS, 474, 411

Evident spurious and known variables already removed

VSTJ57.77559-59.13990 SN Ib/c candidate possibly associated with Fermi-GBM GRB 150827A

SN candidates in the GW150914 VST follow-up



BBH EM counterpart search with VST

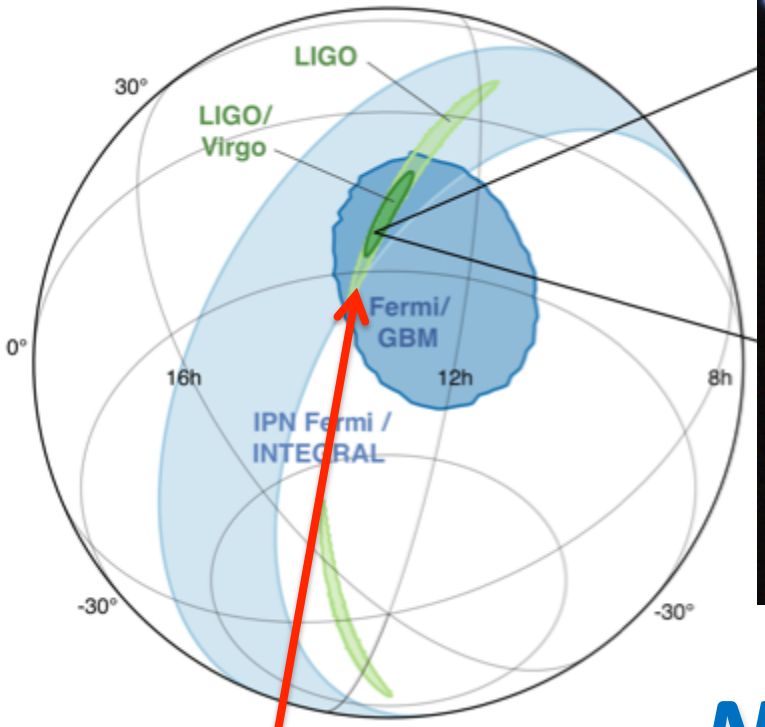
Event	Pipeline	Initial number of sources	optical transients	SNe
GW150914	ph-diff	$9x10^6$	1300	10
	ph-pipe		939	-
GW151226	ph-diff	$9x10^5$	1113	21
	ph-pipe		305	-
GW170814	ph-diff	$1.5x10^6$	55	24
	ph-pipe		37	

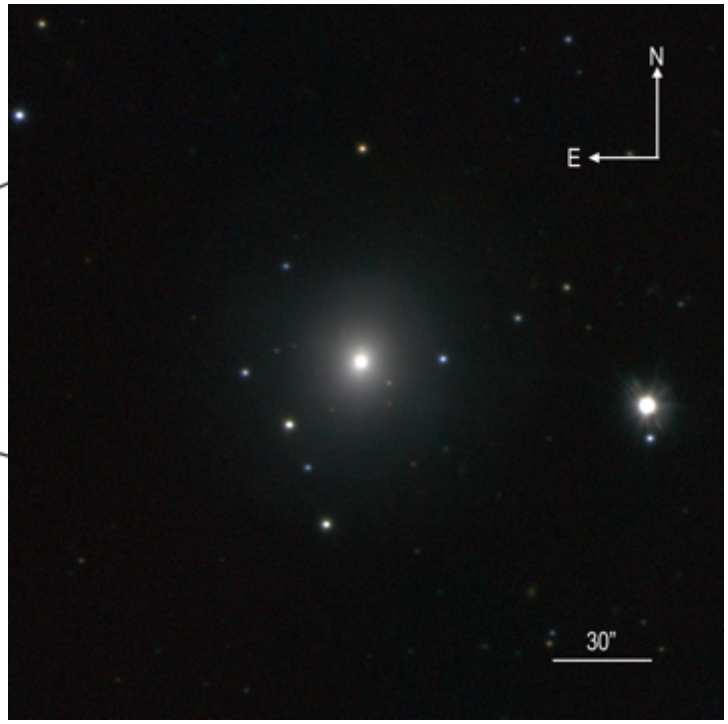
See Sheng's next talk

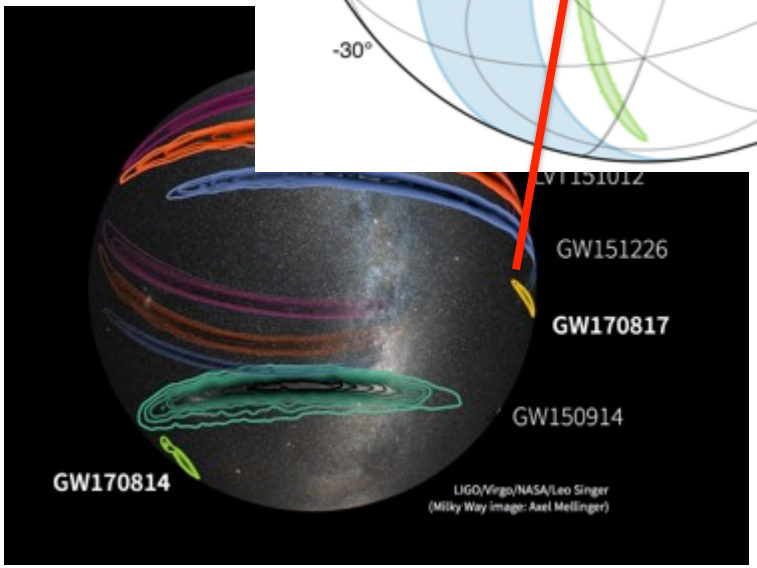
For each event search in 6 epochs distributed over ~ 2 months

The watershed

2017-08-17 12:41:04 UTC





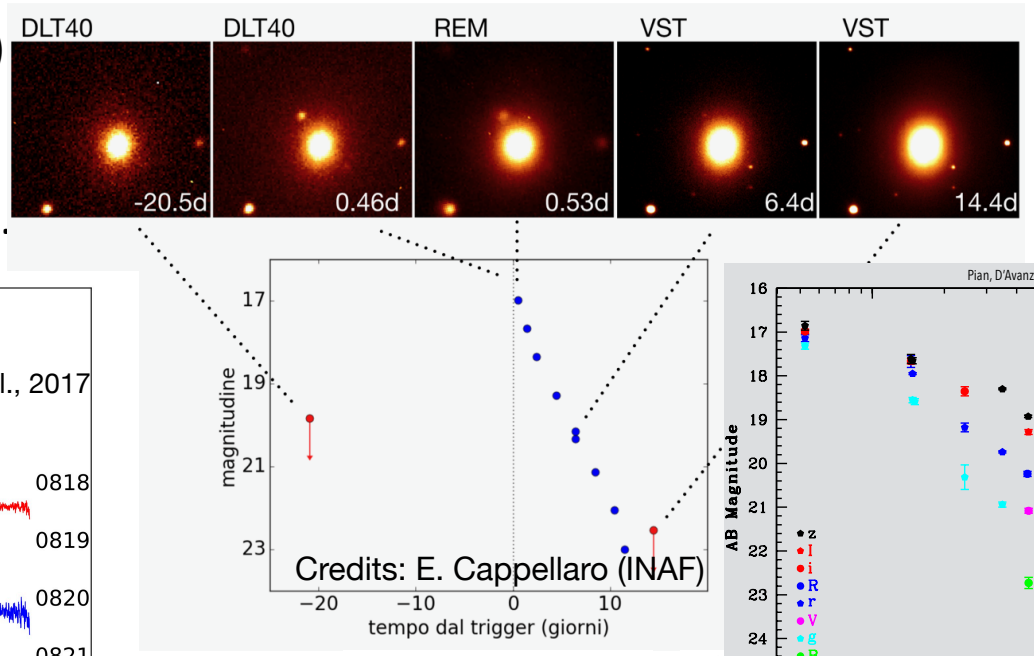


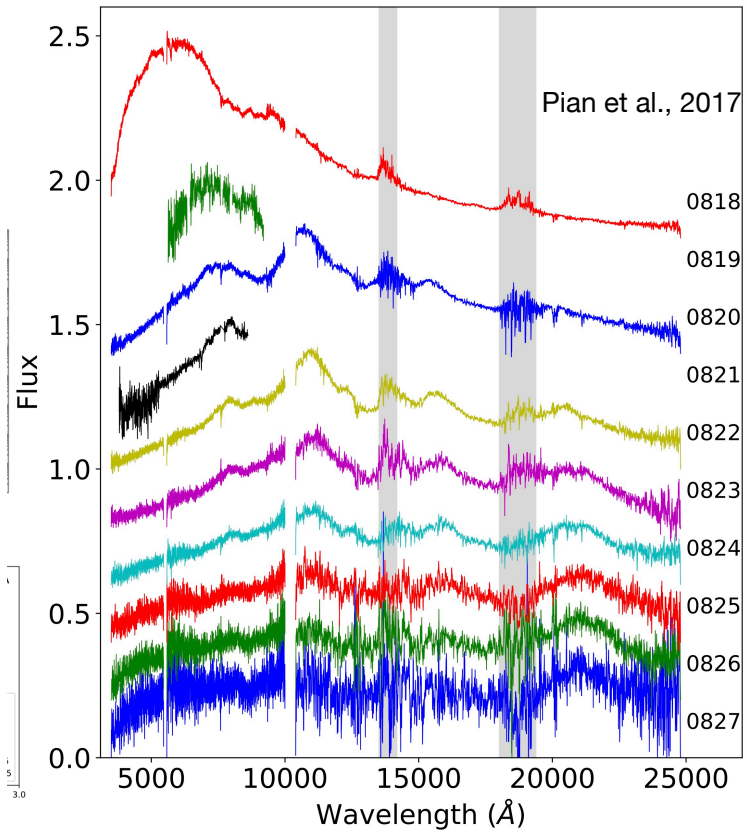
NGC4993@ VST

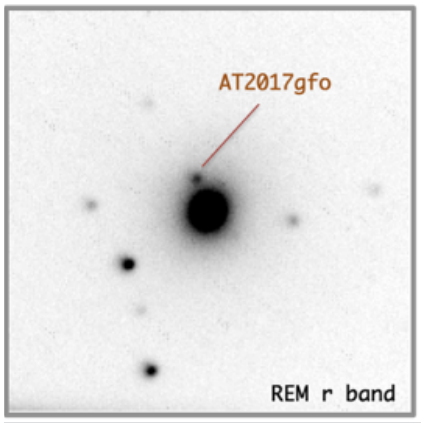
Abbott et al. 2017, PRL, 119, 1101

Grawita's follow up of AT2017gfo

- from 12.8 h to 144 d
- BgVRrIiz (~ 9 h on source)
- Spectroscopy (~15 h on source)
- REM, VST, VLT/X-shooter, VLT/ Fors2
- Not visible from TNG, Asiago, C.







Grawita's follow up of AT2017gfo

- from 12.8 h to 144 d
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- Spectroscopy (~15 h on source)
- REM, VST, VLT/X-shooter, VLT/

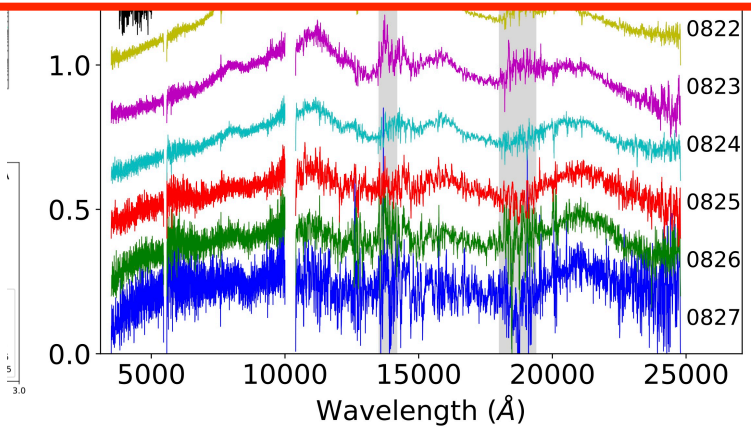
TITLE: GCN CIRCULAR
NUMBER: 21592
SUBJECT: LIGO/Virgo G298048: GRAWITA VLT/X-shooter observations
DATE: 17/08/19 12:16:37 GMT
FROM: Andrea Melandri at INAF-OAB <andy.melandri@gmail.com>

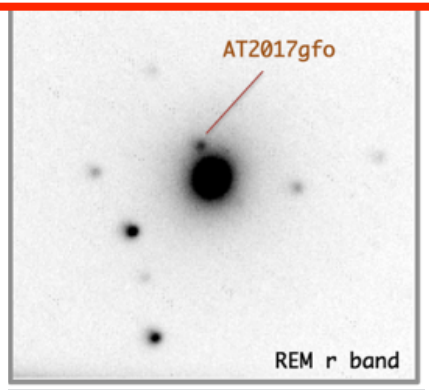
E. Pian (INAF-IASF Bo), V. D'Elia (INAF-ASDC), S. Piranomonte (INAF-OAR), M. Branchesi (GSSI), S. Campana (INAF-OAB), E. Cappellaro (INAF-OAPD), S. Covino (INAF-OAB), P. D'Avanzo (INAF-OAB), A. Grado (INAF-OAC), G. Greco (Urbino University/INFN Firenze), A. Melandri (INAF-OAB), E. Palazzi (INAF-IASF Bo), G. Stratta (Urbino University/INFN Firenze), L . Tomasella (INAF-OAPD), L. Amati (INAF-IASF Bo), L. A. Antonelli, (INAF-OAR), S. Ascenzi (INAF-OAR), S. Benetti (INAF-OAPD), M.T. Botticella (INAF-OAC), D. Fugazza, F. Getman (INAF-OAC), L. Limatola (INAF-OAC), M. Lisi (INAF-OAR), L. Nicastro (INAF-IASF Bo), L. Pulone (INAF-OAR), A. Rossi (INAF-IASF Bo), P. Schipani (INAF-OAC), G. Tagliaferri (INAF-OAB), V. Testa (INAF-OAR), S. Yang (INAF-OAPD), L. Sbordone (ESO) and E. Brocato (INAF-OAR) on behalf of GRavitational Wave Inaf TeAm and the team of the ESO VLT program 099.D-0382(A) report:

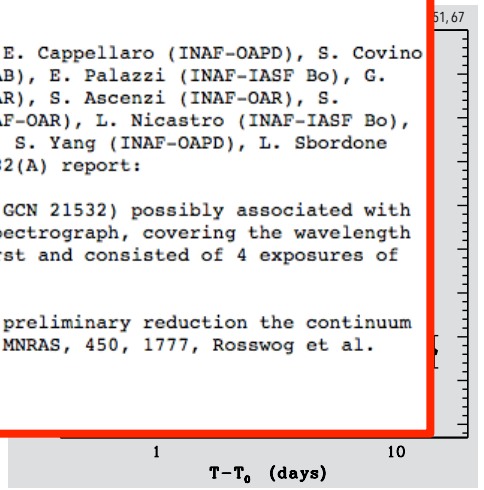
We observed object SSS17a (Coulter et al., GCN 21529; Allam et al., GCN 21530; Yang et al., GCN 21531, Melandri et al., GCN 21532) possibly associated with the LIGO/Virgo event G298048 (GCN 21509), with the ESO Very Large Telescope UT 2 (Kueyen) equipped with the X-shooter spectrograph, covering the wavelength range 3000-25000 AA. Observations started at 23:16 UT on 2017-08-18, during the twilight, roughly 1.5 days after the burst and consisted of 4 exposures of 600 s each.

The transient is bright, well detected in the acquisition image, and clearly visible in all the spectral range. After a preliminary reduction the continuum appears to be similar to that predicted by kilonova models (Tanaka & Hotokezaka 2013, ApJ, 775, 113; Kasen et al. 2015, MNRAS, 450, 1777, Rosswog et al. 2016, arxiv1611.09822). We do not detect any obvious emission lines throughout the spectrum.

Further X-shooter observations are planned.







Grawita's Proposals

- Proposal VST (P102 80 h up to 8 events 30deg^2)
- Proposal LBT 2018B 65h
- Proposal TNG (10/2018-4/2019 90h)
- Asiago, Campo Imperatore
- Proposal ENGRAVE 200 Co-I (P102-P104, 200 h X-shooter, Fors2)
- Proposal ENGRAVE (P102, 10 h MUSE)
- Proposal NOT (P57 14 h)
- REM (AOT37 40 h)

Conclusion

- Exploiting the Italian expertise in wide field imaging, photometric variability, SNe search, GRB follow-up, Radio, theoretical models the GRAWITA group was setup since 2015
- Access to wide set of observing facilities for search and characterization of GW optical/NIR counterparts
- We can do both targeted and blind search
- With VST we plan to follow (six epochs distributed over 2 months) ~ 2.5 to 8 events/semester
- We plan to follow BNS, NS-BH and nearby BBH (100-200 Mpc)

Thanks